The Ion Propulsion System for the Asteroid Redirect Robotic Mission

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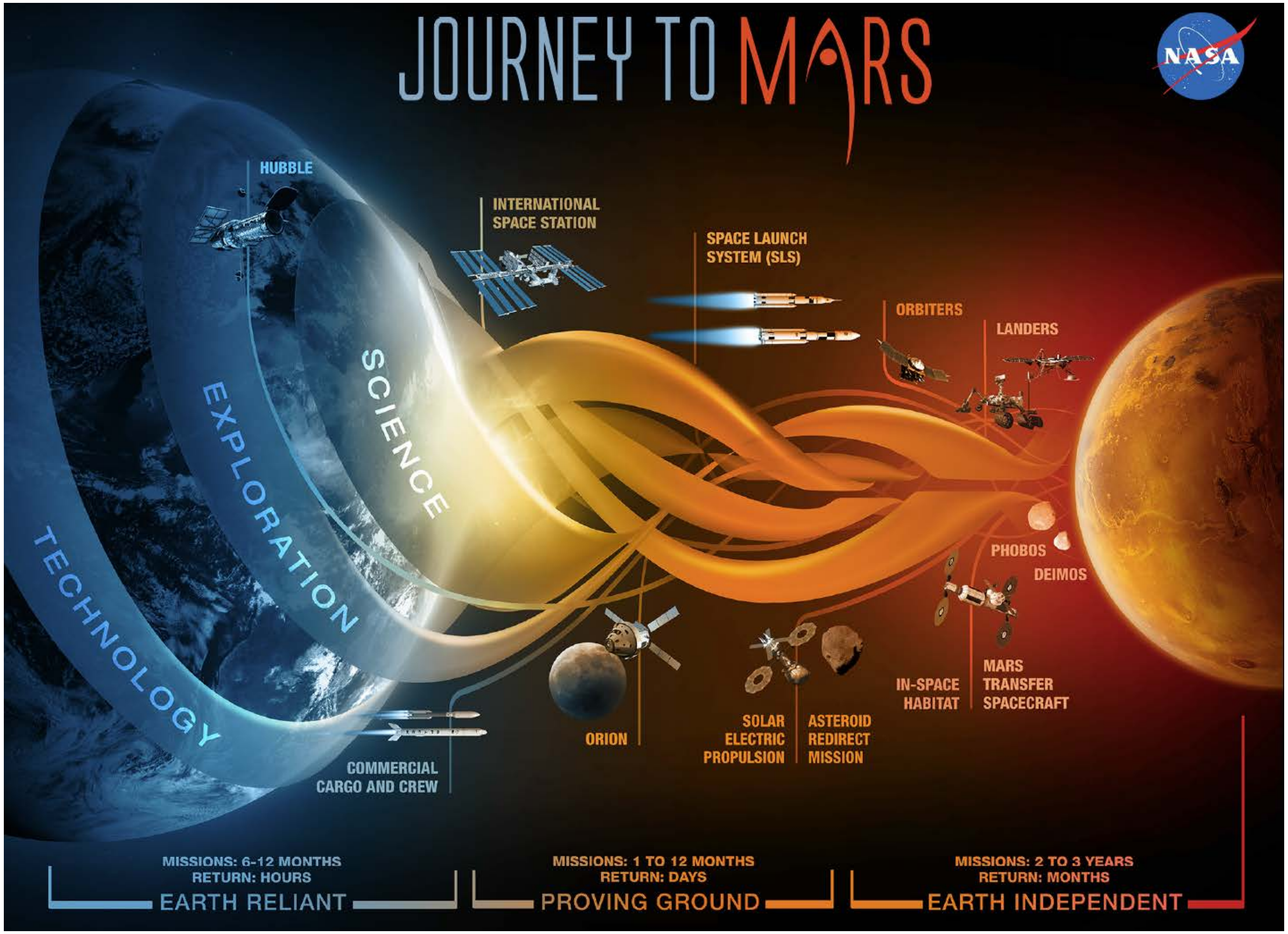
Outline

- EMC, SEP TDM, and ARRM
- Ion Propulsion System Overview
- NASA In-House Technology Development Status
  - 12.5 kW HERMeS Thruster
  - 13.3 kW HP-120V PPU
- Transition-to-Flight
  - Advanced Electric Propulsion Contract
  - ARRM Spacecraft
- Conclusions

High-Power SEP Critical to NASA Exploration Vision

- High-Power SEP systems required to move large masses in interplanetary space
  - Leveraged in a multi-use, evolvable space infrastructure

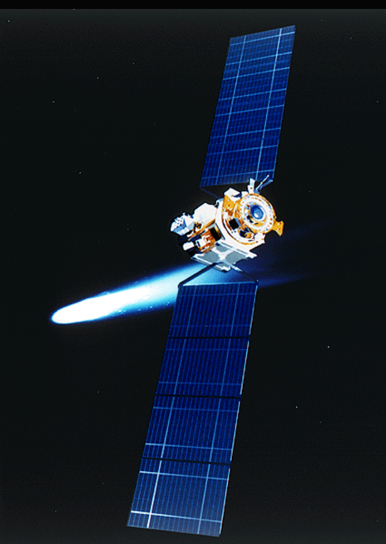


Credit: NASA's Journey to Mars " NP-2015-08-2018-HQ, http://www.nasa.gov/sites/default/files/atoms/files/journey-to-mars-next-steps-20151008_508.pdf, 2015.

High-Power SEP Module Extensibility for Mars

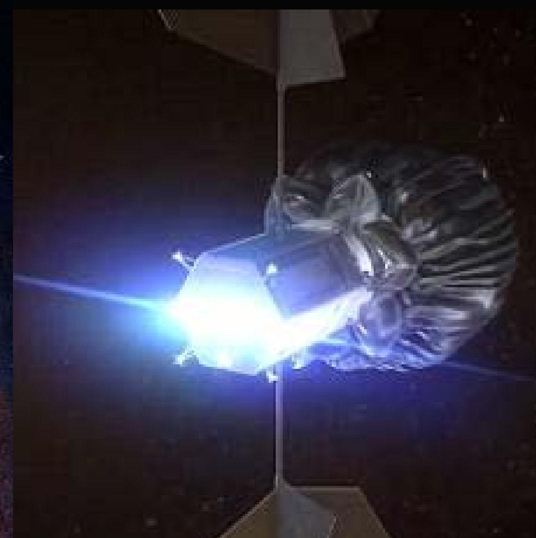
50kW-class spacecraft w/advanced solar arrays and electric propulsion

- Transportation capability with fuel efficiency 10x chemical systems
- Reduces trip times by 5x relative to existing SEP systems
- Scales to higher power to support beyond LEO human exploration



1998 Deep Space 1
Technology Demonstrator
374kg dry/82kg Xe
2.5 kW power system
2.5kW EP system
1900-3200s specific impulse

2007 Dawn
Deep-Space Science Mission
747kg dry/425kg Xe
10 kW power system
2.5kW EP system
1900-3200s specific impulse

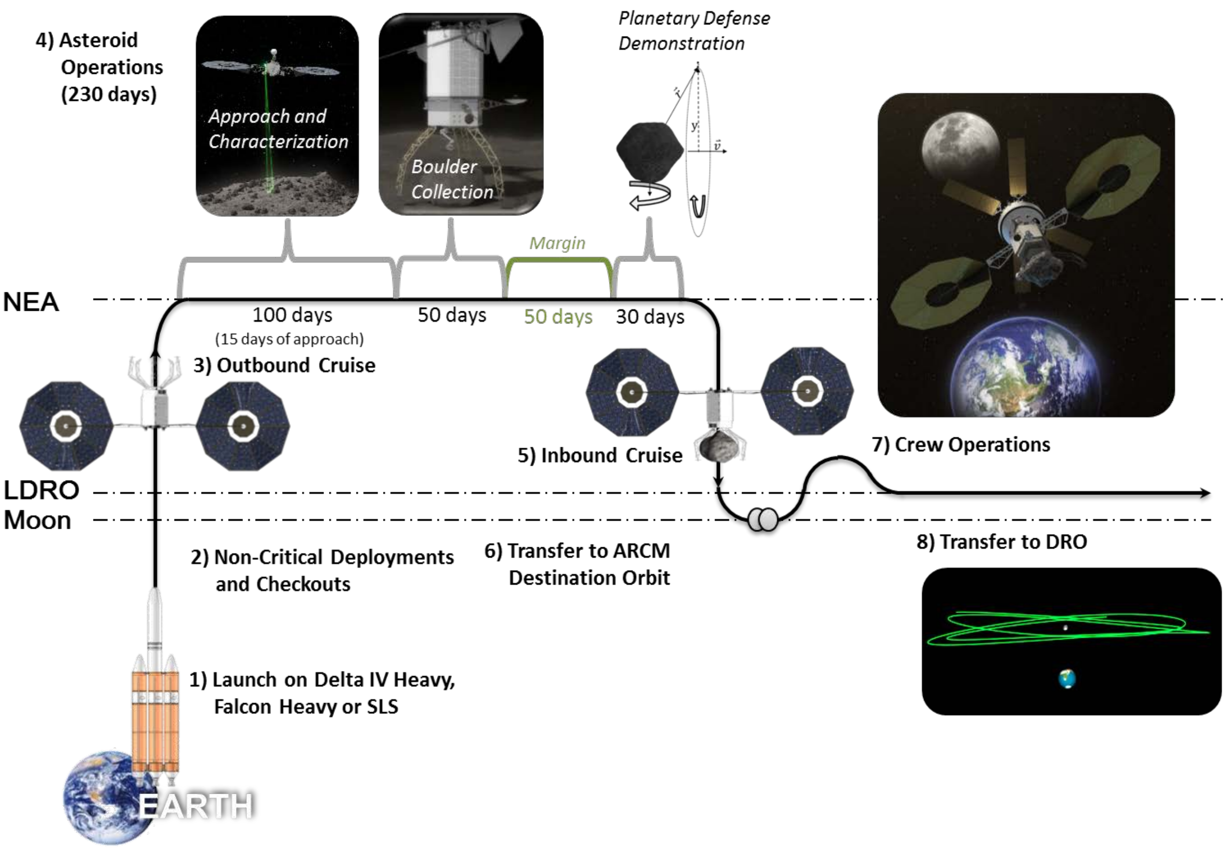


~2020 SEP TDM
Asteroid Redirect Mission
4,500 kg dry/5,000kg Xe
50kW power system
40kW EP system
2000-3000s specific impulse

≥ 2025 Beyond LEO Human Exploration
Prepositioning of assets
~7000kg dry/16,000kg Xe
~200kW power system
150kW EP system
2000-3000s specific impulse

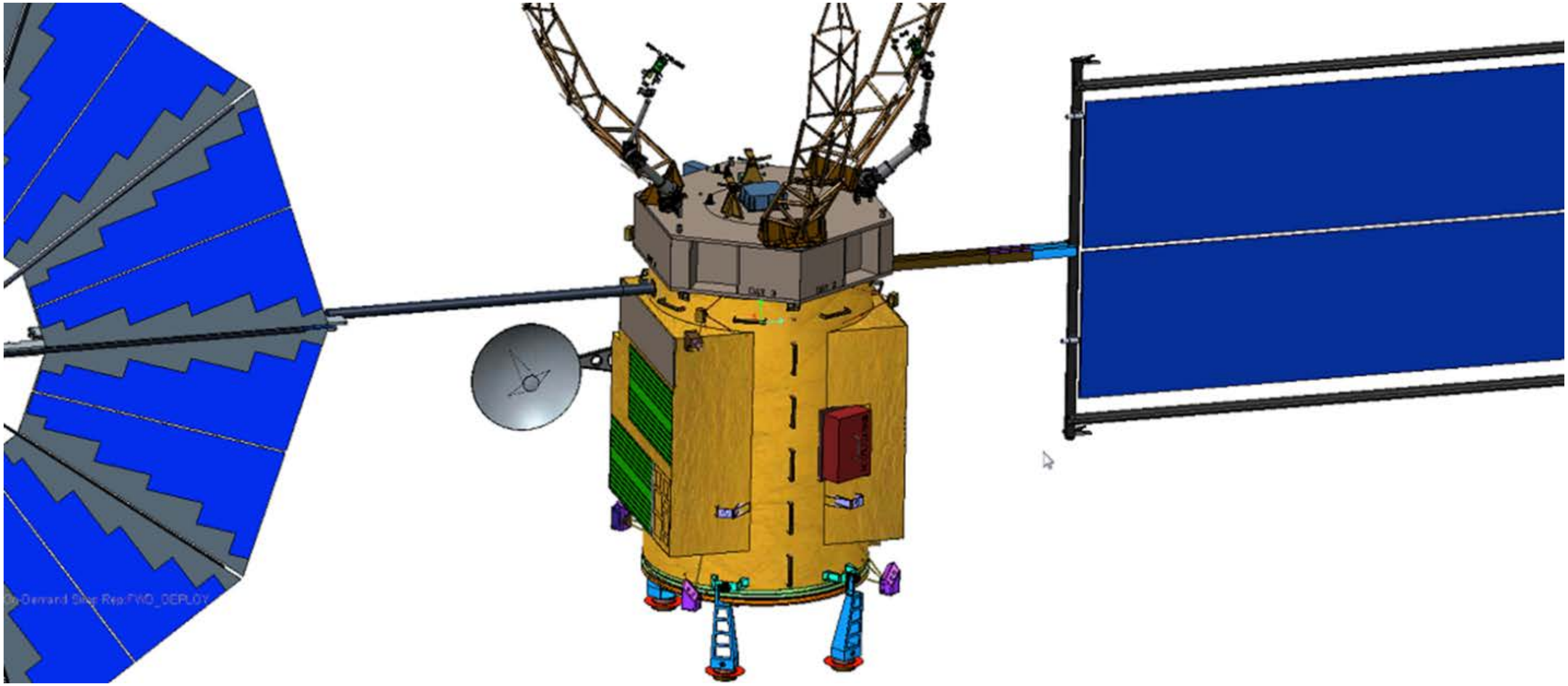
Solar Electric Propulsion Technology Demonstration Mission

- High-power SEP can be enabling for both near-term and future exploration architectures and science missions
- NASA is maturing mission design for a 50kW-Class SEP Demonstration
  - Most mature concept is the Asteroid Redirect Robotic Mission



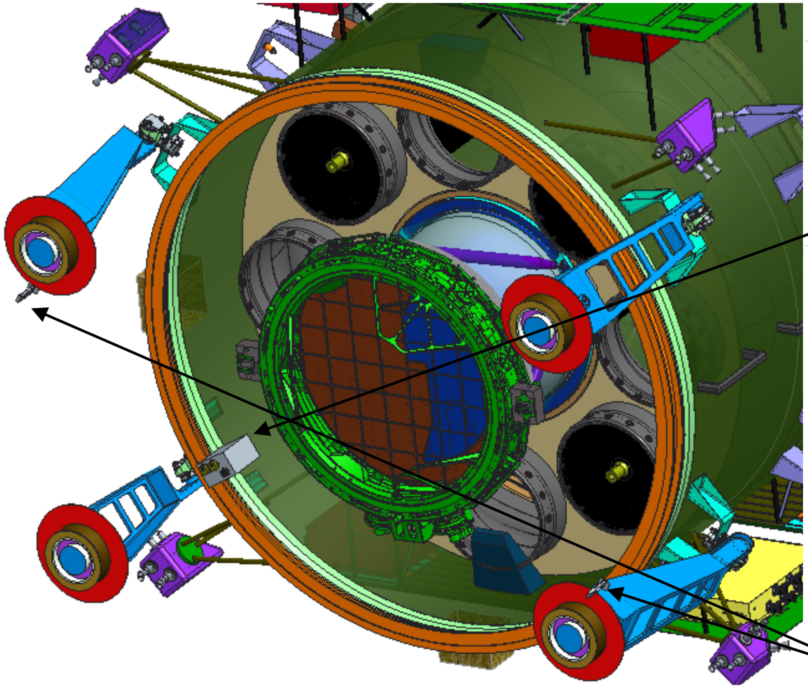
- Dec. 2021 launch
- 2026 asteroid boulder return to cis-lunar space
- Reference asteroid: 2008 EV_5
- Electric propulsion used for:
  - Maneuver for LGA
  - Heliocentric transfer to and from asteroid
  - Orbit capture/transfer at asteroid
  - Planetary defense demo
  - Departure/escape from asteroid
  - Insertion into lunar DRO
  - Pitch and yaw control of vehicle during EP operation

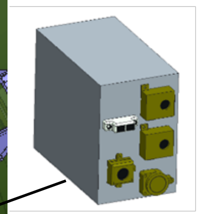
NASA Asteroid Redirect Vehicle Conceptual Design



- Ability to utilize multiple advanced, deployable solar array technologies currently being matured
  - MegaFlex and ROSA wings shown
- EP thrusters shown on gimbal with boom
  - Reduce plume impingement on the vehicle (especially docking ring and solar arrays)
  - Beneficial for large off-axis thrusting for planetary defense demonstration
- Capability of carrying in excess of 10 tons of xenon, but loaded only to 5.3 tons
- Leverages synergy with Restore-L service mission: rendezvous and proximity operations sensors, dexterous robotics, hybrid flight computing algorithms, and servicing avionics

Conceptual ARRM Plasma Diagnostics Package

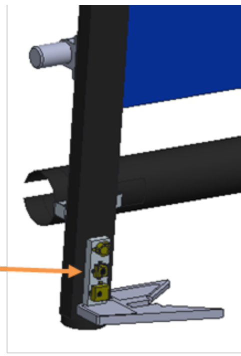




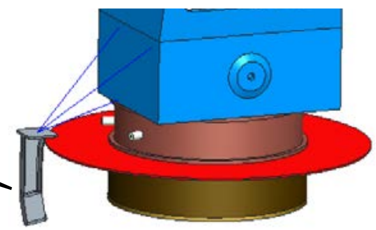
Tower

1. Retarding Potential Analyzer for ion energy distribution
2. Planar Langmuir Probe/Faraday Probe for plasma density, potential and electron temperature
3. Gridded Faraday Probe/Flux Sensor for ion flux
4. Erosion sensor for sputtering from ion bombardment
5. Photometer tor deposition of sputtered material

Sensors on Array Wing



1. Retarding Potential Analyzer
2. Planar Langmuir Probe/Faraday Probe
3. Erosion sensor



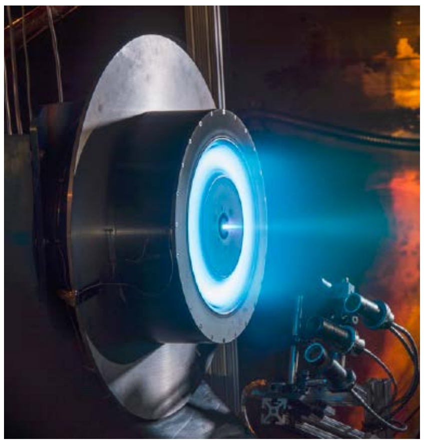
High-Speed Probe

1. Planar Langmuir Probe/Faraday Probe for ion current, plasma density, plasma potential, and electron temperature measurements (Sensor downstream of thruster exit plan with line-of-site to discharge plasma)

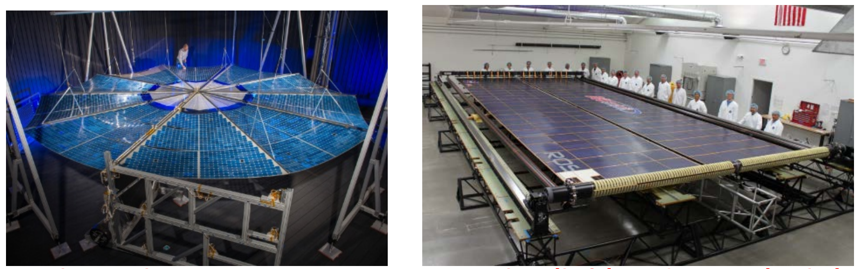
- Collect high-value plasma plume data
  - Validate models of high-power SEP operation and spacecraft plasma interactions
  - Improve design tools that are critical to enabling high-power SEP spacecraft to support future human and robotic missions to Mars
  - Provide in-flight SEP system performance measurements and thruster characterization tool
  - Measure surface erosion and material re-deposition
- Government-led development of package provided as GFE to mission
  - Utilizes high-heritage instruments flown on prior NASA and other government spacecraft

High-Power SEP Technology Investments

- NASA is developing the requisite technologies for a 50kW-Class Solar Electric Propulsion Demonstration to enable SEP missions and applications at higher power levels

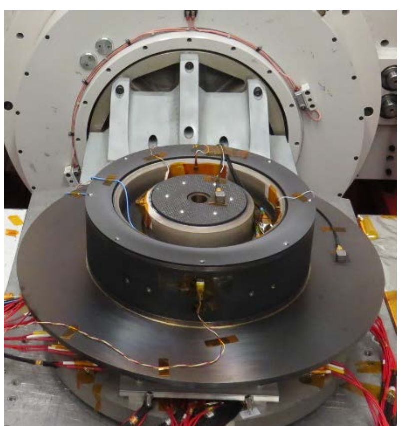


12.5kW HERMES TDU-1

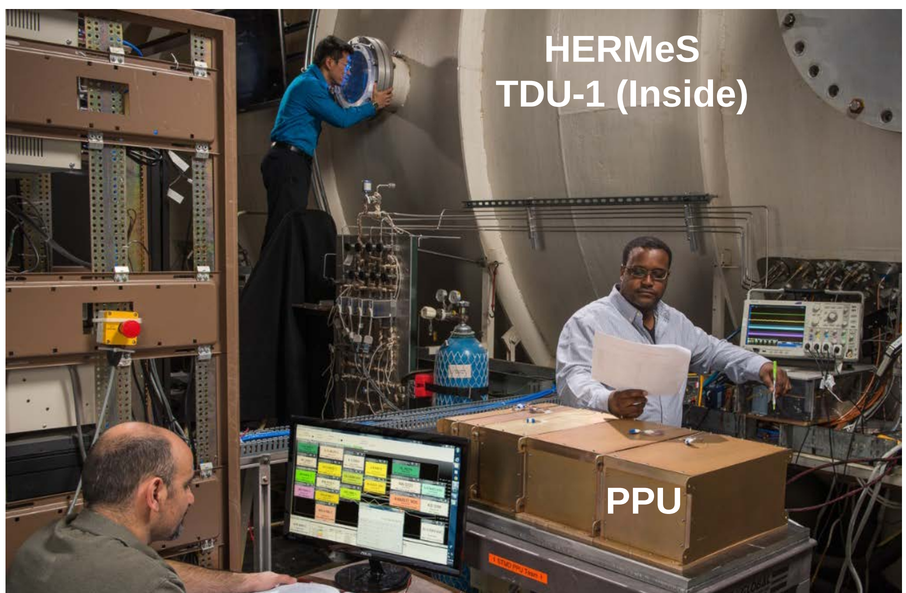


25-kW Solar Array Structures: MegaFlex (left) and ROSA (right)

HP-120/800V Brassboard PPU

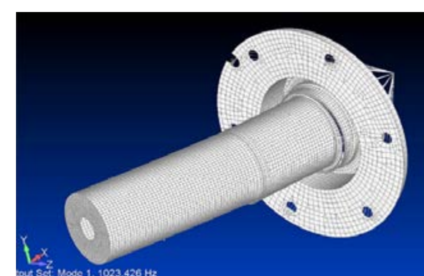


12.5kW HERMES TDU-2



HERMeS TDU-1 and PPU Integration Test (NASA VF5)

LaB_6 Cathode



BaO Cathode

Ion Propulsion System and Thruster Requirements

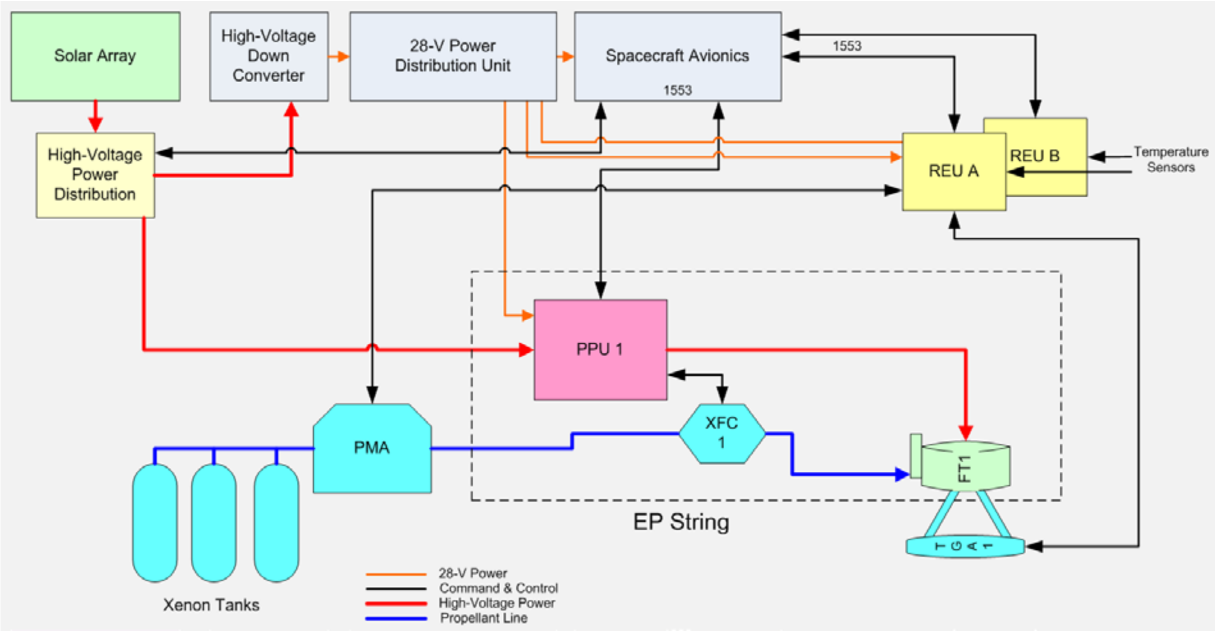
- Key ARRM Requirements for Ion Propulsion System (IPS)

Capability	Value
Total system power	40 kW
Maximum specific impulse	2600 s
Xenon throughput	5,000 kg
String fault tolerance	Single
Solar range	0.8 – 1.7 AU
Input voltage range	95 – 140 V

- Simplified EP String throttling utilized in ARRM mission design
  - ARRM mission analyses shown that maximum boulder return mass and xenon propellant required vary by less than 5% and 2%, respectively over 2,600 – 3,000 s specific impulse range

EP String Total Input Power (kW)	Discharge Voltage (V)	Thrust (mN)	Mass Flow Rate (mg/s)	System Efficiency
13.3	600	589	22.9	0.57
11.1	500	519	22.0	0.55
8.9	400	462	22.1	0.54
6.7	300	386	21.7	0.52
3.4	300	200	11.9	0.49

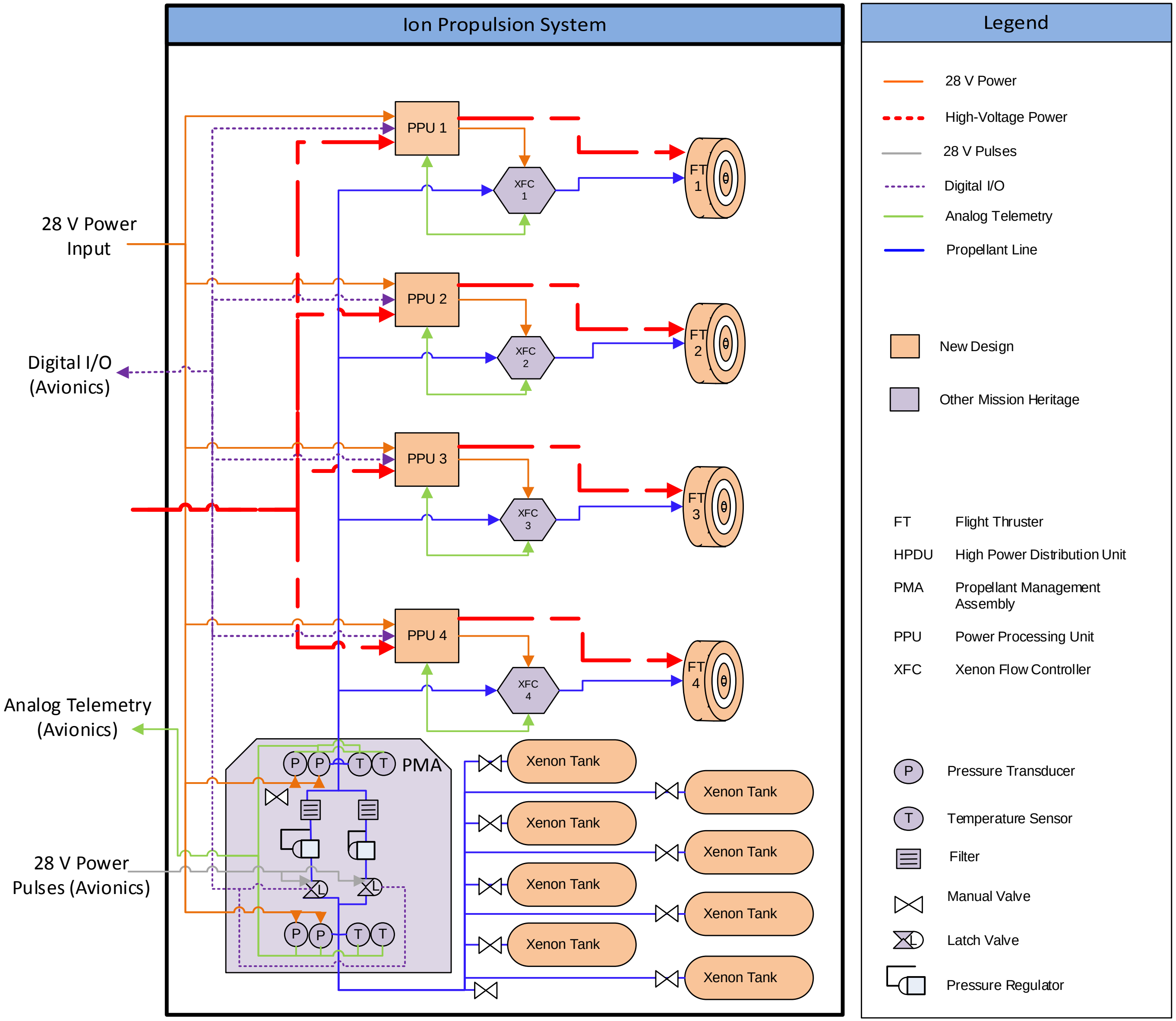
Government-Furnished Electric Propulsion String



Legend:
REU: Remote Engineering Unit
TGA: Thruster Gimbal Assembly
FT: Flight Thruster
XFC: Xenon Flow Controller
PPU: Power Processing Unit
PMA: Propellant Management Assembly
28V: Low Voltage Bus

- GFE Electric Propulsion String consists of:
  - Flight Thrusters (FT)
  - Power Processing Unit (PPU)
  - Xenon Feed System (XFS)
  - Harnesses between the above elements
- Thruster gimbal is not considered part of the GFE EP string
  - Gimbal design specific to spacecraft configuration still being matured

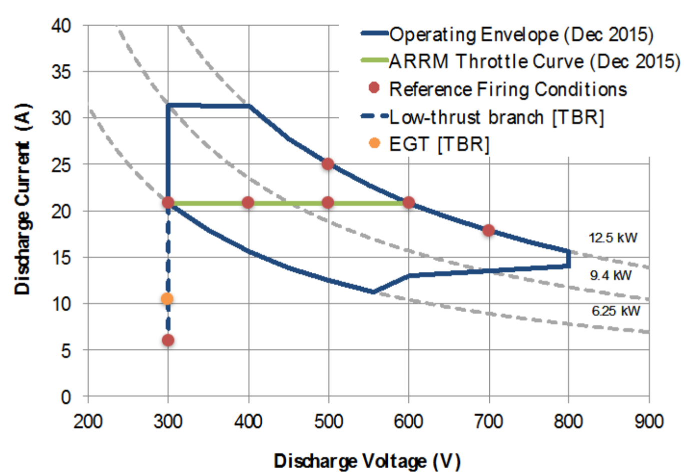
IPS Functional Block Diagram

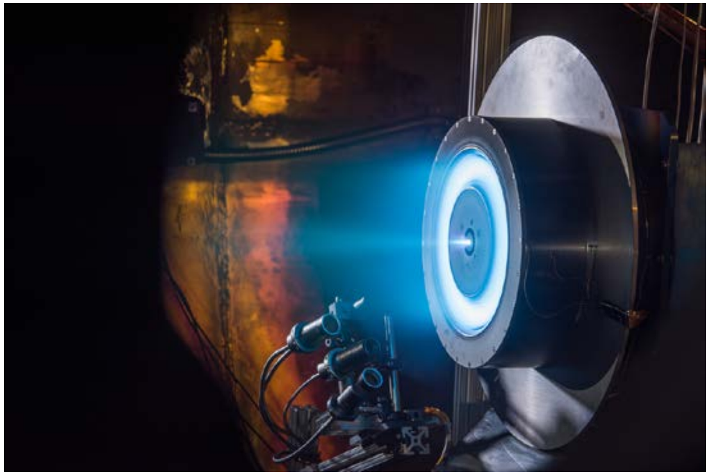


- 3+1 EP Strings consisting of four elements
  - Flight Thrusters (FT)
  - Power Processing Unit (PPU)
  - Xenon Feed System (XFS)
  - Mechanical Integration Hardware (MIH)
- Thruster gimbal is part of spacecraft structures and mechanisms

HERMeS Thruster Development Status

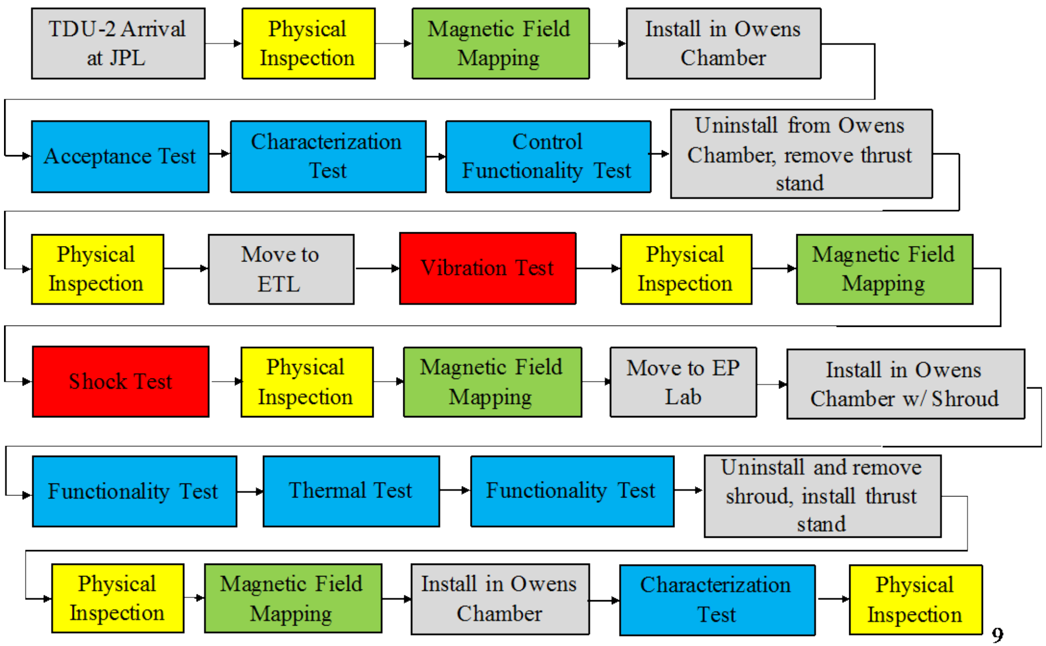
- NASA GRC and JPL developed 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS) to demonstrate viability and address mission risks
- First Technology Demonstration Unit (TDU-1) fabricated and extensively tested
  - Operating envelope (blue) spans 300-800 V, 8.9-31.3 A (3.5:1), & 6.25-12.5 kW
  - TDU-1 testing has demonstrated operating points (red) as low as 300 V, 2 A
    - Performance and plume mapping: including facility effects characterizations, magnetic field strength optimization, magnetic field symmetry assessment, cathode flow fraction characterization, and plume flux, energy, and charge state
    - Multiple thermal characterizations to quantify thermal margin
    - Wall probe measurements to verify magnetic shielding require for long-life
  - **TDU-1 is approximately 1,000 hours into a 2,000 hour wear test in VF5**



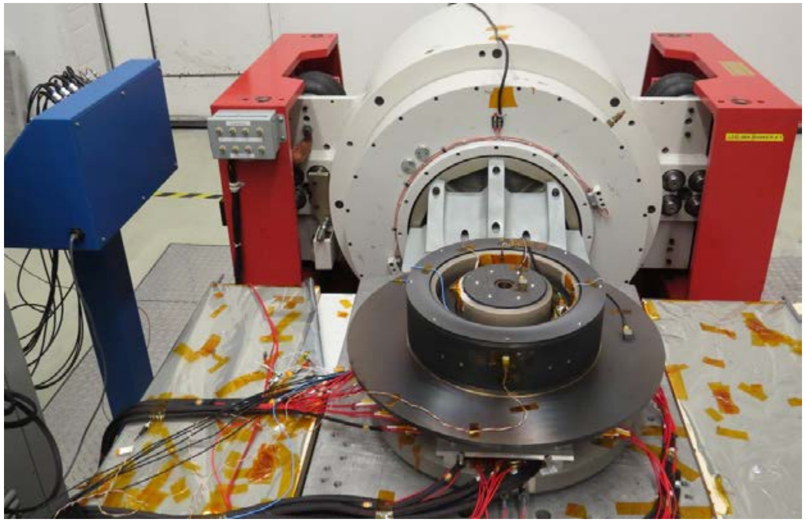


HERMeS Thruster Development Status

- A second Technology Demonstration Unit (TDU-2) was fabricated at NASA GRC for an environmental test campaign at JPL with the following modifications
  - Improved thermal management relative to TDU-1
  - Structural modifications for surviving dynamic environments

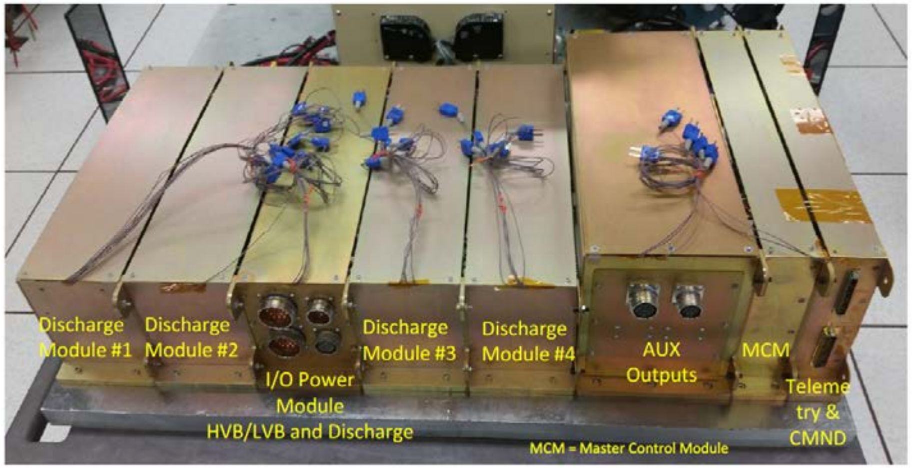


Test Flow for TDU-2 Environmental Test Campaign at JPL

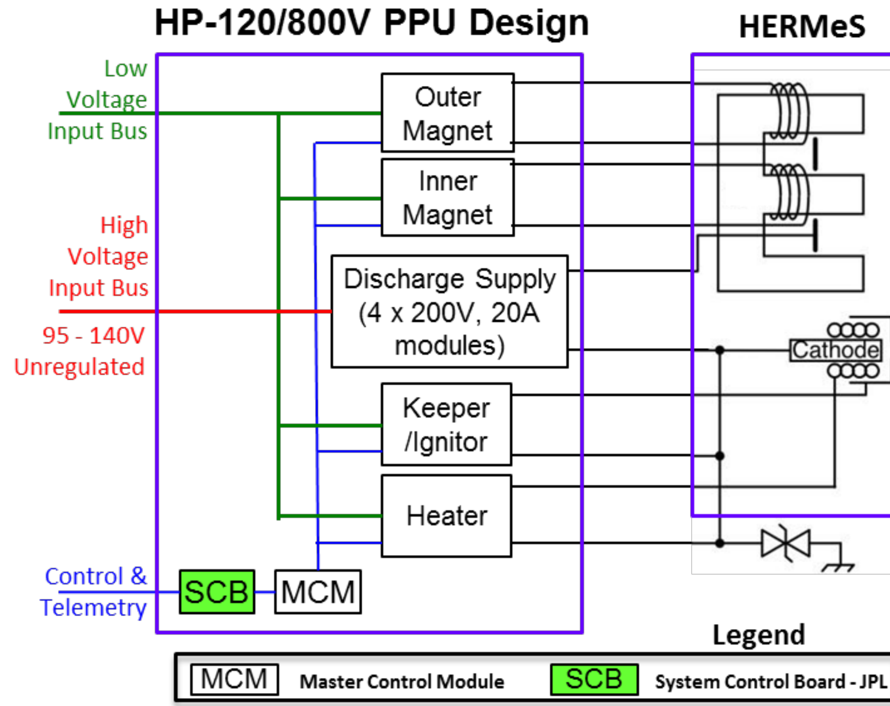


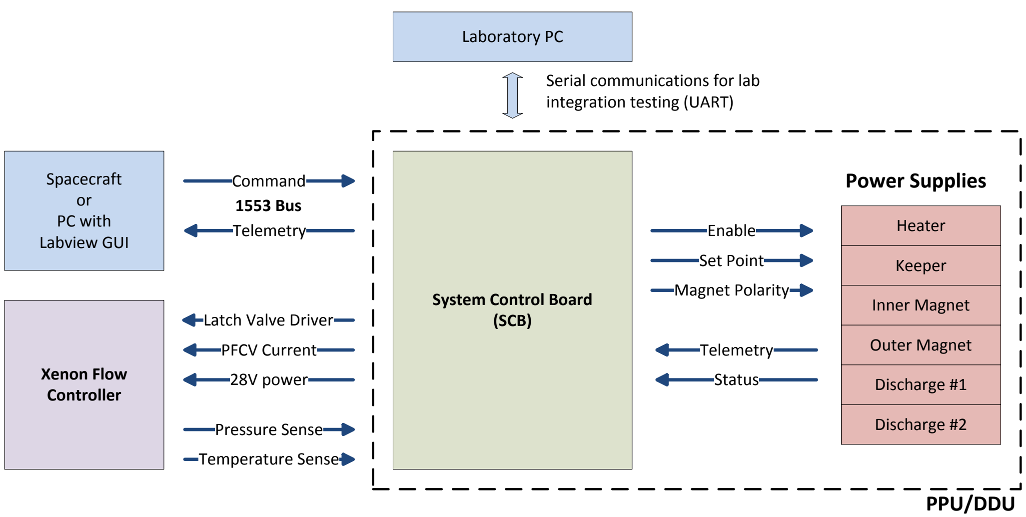
TDU-2 Installed on Vibe Table at ETL

HP-120V PPU Development Status



14 kW HP-120V Full-Bridge Topology Power Processing Unit (PPU)

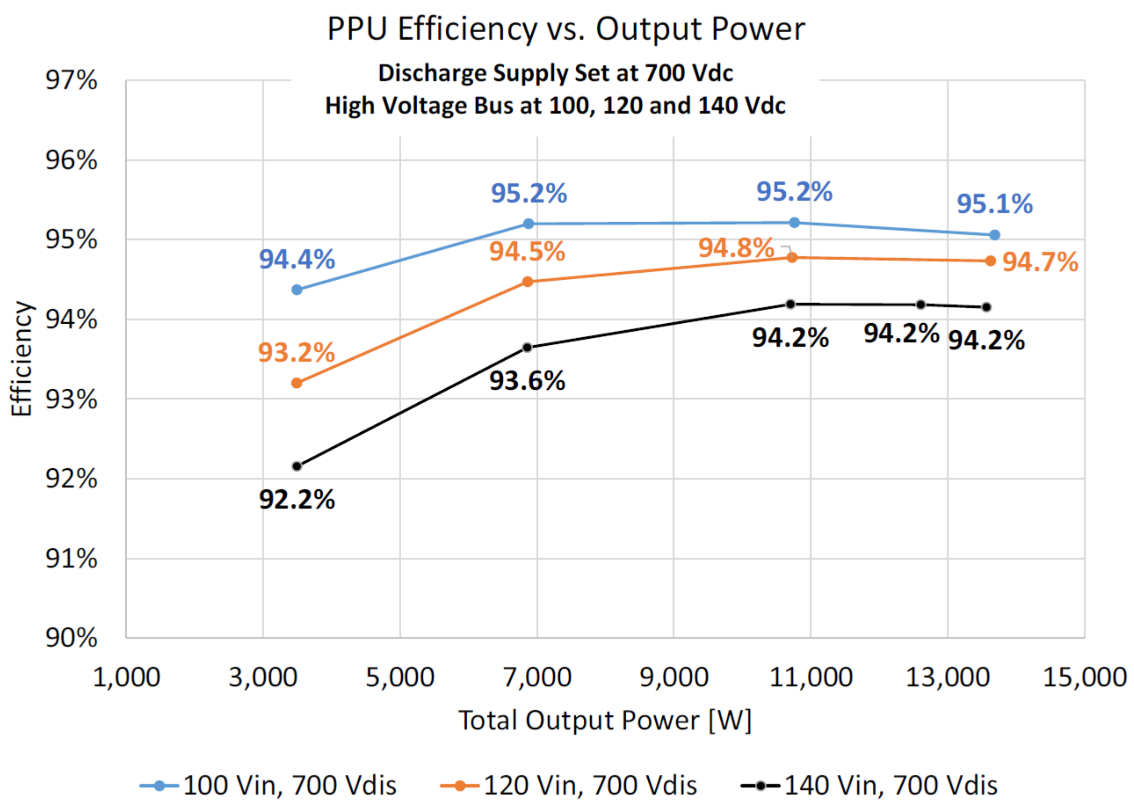




System Control Board (SCB) developed and undergoing integration in HP-120V PPU

- EP string command, control, and telemetry interface

HP-120V PPU Development Status



- Brassboard unit developed and tested over operating range 2 – 14 kW, 95 – 140 V input, and 200 – 800 V output
  - Ambient functional testing
  - Vacuum performance characterization: 5 – 50 ° C cold plate range
  - Integrated testing with TDU-1 HERMeS thruster: ignition, transient and steady-state characterization; output filter optimization; and input power quality characterization

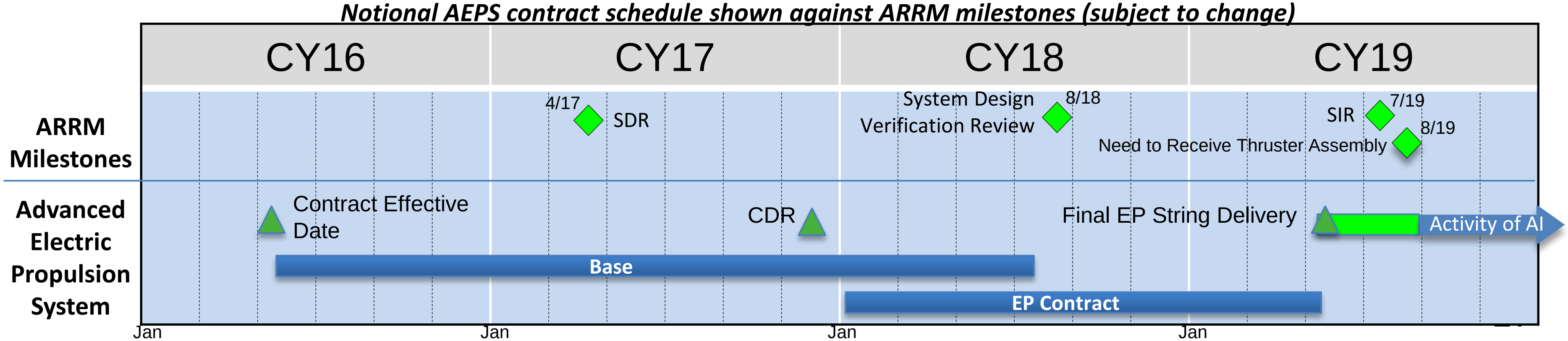
HERMeS Thruster & PPU Development Status

- Monday [July 25]
  - [11:30 – 12:00] J.L. Myers; H. Kamhawi; J. Yim; L. Clayman, “Hall Thruster Thermal Modeling and Test Data Correlation”
- Tuesday [July 26]
  - [3:00 – 3:30] C. Marrese-Reading, “Life Testing of a Tantalum-sheathed Heater with Alumina Insulation for LaB6 Hollow Cathodes”
  - [3:30 – 4:00] R.R. Hofer, “Development Status of the 12.5 kW HERMeS Hall thruster for the Solar Electric Propulsion Technology Demonstration Mission”
  - 3:30 – 4:00] J.E. Polk, “Effect of Oxygen-contaminated Xenon Flow to the Operation of a Lanthanum Hexaboride Hollow Cathode”
  - [4:00 – 4:30] H. Kamhawi, “Performance and Stability Characterization Tests of NASA’s 12.5-kW Hall Effect Rocket with Magnetic Shielding Thruster”
  - [4:00 – 4:30] D.M. Goebel, “Lanthanum Hexaboride Hollow Cathode Performance and Wear Testing for the Asteroid Redirect Mission Hall Thruster”
  - [4:30 – 5:00] R.W. Conversano, “Performance and Characterization of the 12.5 kW HERMeS Hall Thruster during Environmental Testing”
  - [5:00 – 5:30] W. Huang, “Facility Effect Characterization Test of NASA’s HERMeS Hall Thruster
  - [5:00 – 5:30] P. Guerrero, “The Effect of Orifice Size on Lanthanum Hexaboride Hollow Cathode Performance and Thermal Behavior”
  - [5:30 – 6:00] W. Huang, “Plasma Oscillation Characterization of NASA’s HERMeS Hall Thruster via High Speed Imaging”
- Wednesday [July 27]
  - [9:30 – 10:00] M.J. Sekerak, “Modeling of Plasma Plume Interaction with a Spacecraft Operating High-Power Hall Effect Thrusters”
  - [11:00 – 11:30] J.E. Polk, “Hollow Cathode Operation with Time-Varying Currents”
  - [11:30 – 12:00] J.H. Gilland, “Carbon Back Sputter Modeling for Hall Thruster Testing”
  - [3:00 – 3:30] M.J. Sekerak, “Environmental Testing of the 12.5 kW HERMeS Hall Thruster for a proposed Solar Electric Propulsion Technology Demonstration Mission
  - [3:30 – 4:00] G. Williams, “2000-hour Wear-Testing of the HERMeS Thruster”
  - [4:00 – 4:30] J.E. Polk, “Inner Front Pole Erosion in the HERMeS Thruster Over a Range of Operating Conditions
  - [4:30 – 5:00] T.R. Sarver-Verhey, “Hollow Cathode Assembly Development for the HERMeS Hall Thruster”
  - [5:00 – 5:30] P.Y. Peterson, “2,000 Hour Wear Assessment of the HERMeS BaO Hollow Cathode”
  - [5:30 – 6:00] N. Yanes, “Ion Acoustic Turbulence and Ion Energy Measurements in the Plume of the HERMeS Thruster Hollow Cathode”
  - [5:30 – 6:00] W. Santiago, “High Input Voltage, Power Processing Unit Performance Demonstration”

Government-Furnished EP String

- A competitively-selected cost-plus fixed fee including incentives contract was initiated to develop and procure the EP strings that will be provided as GFE to ARRM
  - Draft Request for Proposals (RFP) issued on May 5, 2015
    - Base Period of Performance includes:
      - (1) Engineering Development Unit (EDU) EP String including GSE & (1) additional EDU Hall thruster
    - Option Period of Performance includes:
      - (1) Qualification Model (QM) EP String
      - (4) Flight Model (FM) EP Strings including GSE & (1) Spare FM PPU
- The Advanced Electric Propulsion System (AEPS) $65M contract plus up to $2M incentives was awarded to Aerojet Rocketdyne with subcontractors ZIN Technologies and VACCO Industries
  - May 16, 2016 Authority to Proceed

Notional AEPS contract schedule shown against ARRM milestones (subject to change)



Asteroid Redirect Vehicle Acquisition

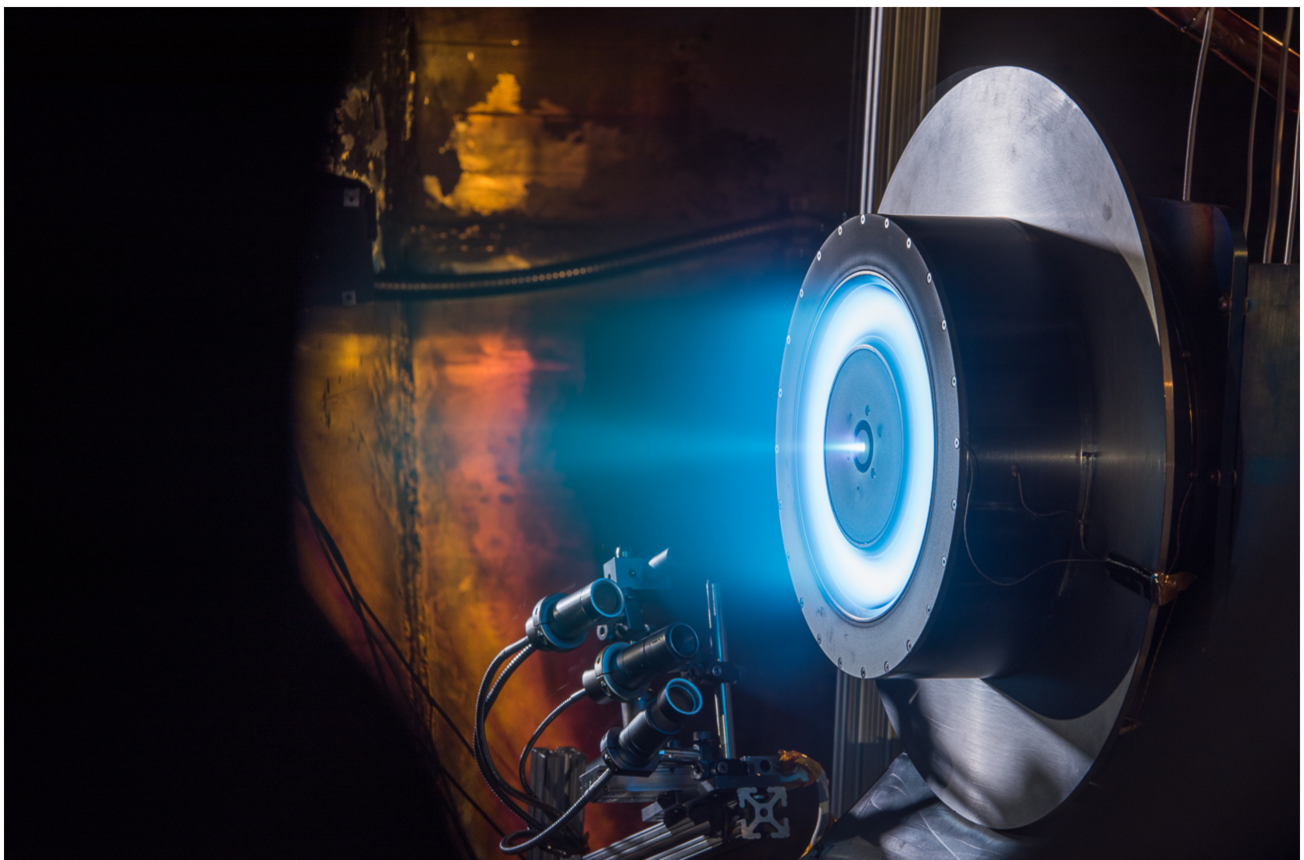
- Asteroid Redirect Vehicle (ARV) Acquisition strategy leverages commercially available U.S. industry capabilities to reduce costs
  - Procurement of ARRM spacecraft occurs in two phases
- Phase 1: Fixed price design study contracts were awarded for to support mission formulation in cooperation with ARRM
  - Lockheed Margin Space Systems
  - Boeing Phantom Works
  - Orbital ATK
  - Space Systems / Loral
- Phase 2: Competitive selections for the development and implementation of the flight spacecraft bus by one of the study participants
  - Request for Proposals for potential procurement in planning phase
  - AEPS GFE String description document and plasma plume description included to define EP string components and interfaces/interactions with vehicle

Conclusions

- NASA is developing high-power SEP systems required to move large masses in interplanetary space as part of a multi-use, evolvable space infrastructure
- NASA is maturing mission design for a 50kW-Class SEP Demonstration
  - Most mature concept is the Asteroid Redirect Robotic Mission
- NASA is developing the requisite technologies for the SEP TDM, including ARRM, to enable these SEP missions that is extensible to applications at even higher power levels
  - Joint NASA GRC and JPL in-house development of the 12.5 kW HERMeS thruster and 13.3 kW HP-120V power processing unit
- The AEPS contract for the development and delivery of 4 flight Electric Propulsion Strings was awarded on May 16, 2016 to Aerojet Rocketdyne
  - Acquisition initiated during ARRM mission formulation to meet the Dec. 2021 ARRM launch date
  - EP strings will be provided as GFE to ARRM
- Phase 1 of ARRM vehicle acquisition completed and Phase 2 in planning
  - Leverages commercially available U.S. industry capabilities to reduce costs
  - EP string description documents detail interfaces between EP string and ARV

Acknowledgements

The support of the joint NASA GRC and JPL development of HERMeS by NASA's Space Technology Mission Directorate through the Solar Electric Propulsion Technology Demonstration Mission (SEP TDM) project is gratefully acknowledged.



12.5kW HERMES TDU-1 inside VF5 at NASA Glenn Research Center (May 2015)

NASA

SEP TDM supported papers at 2015 JANNAF, IEPC, & JPC

[1] Goebel, D. M., Polk, J. E., Mikellides, I. G., and Lopez Ortega, A., "Lanthanum Hexaboride Hollow Cathode for the Asteroid Retrieval/Redirect Mission " Presented at the 34th International Electric Propulsion Conference, IEPC-2015-043, Kobe, Japan, July 4-10, 2015.

[2] Herman, D. A., Polk, J. E., Hofer, R. R., Santiago, W., Kamhawi, H., Scheidegger, R., and Pinero, L., "The Development of the Ion Propulsion System for the Solar Electric Propulsion Technology Demonstration Mission " Presented at the 34th International Electric Propulsion Conference, IEPC-2015-008, Kobe, Japan, July 4-10, 2015.

[3] Herman, D. A. and Unfried, K. G., "Xenon Acquisition Strategies for High-Power Electric Propulsion NASA Missions," Presented at the 62nd JANNAF Propulsion Meeting, JANNAF-2015-XXXX, Nashville, TN, June 1-5, 2015.

[4] Hofer, R. R., Herman, D. A., Polk, J. E., Kamhawi, H., and Mikellides, I. G., "Development Approach and Status of the 12.5 kW HERMeS Hall Thruster for the Solar Electric Propulsion Technology Demonstration Mission," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-186, Kobe, Japan, July 4-10, 2015.

[5] Hofer, R. R., Kamhawi, H., Mikellides, I. G., Herman, D. A., Polk, J. E., Huang, W., Yim, J., Myers, J., and Shastry, R., "Design Methodology and Scaling of the 12.5 kW HERMeS Hall Thruster for the Solar Electric Propulsion Technology Demonstration Mission," Presented at the 62nd JANNAF Propulsion Meeting, JANNAF-2015-3946, Nashville, TN, June 1-5, 2015.

[6] Huang, W., Yim, J. T., and Kamhawi, H., "Design and Empirical Assessment of the HERMeS Hall Thruster Propellant Manifold," Presented at the 62nd JANNAF Propulsion Meeting, JANNAF-2015-XXXX, Nashville, TN, June 1-5, 2015.

[7] Kamhawi, H., Haag, T., Huang, W., Herman, D. A., Thomas, R., Shastry, R., Yim, J., Chang, L., Clayman, L., Verhey, T., Griffiths, C., Myers, J., Williams, G., Mikellides, I. G. et al., "Performance Characterization of the Solar Electric Propulsion Technology Demonstration Mission 12.5-kW Hall Thruster," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-007, Kobe, Japan, July 4-10, 2015.

[8] Kamhawi, H., Haag, T., Huang, W., and Hofer, R. R., "The Voltage-Current Characteristics of the 12.5 kW Hall Effect Rocket with Magnetic Shielding at Different Background Pressure Conditions," Presented at the 62nd JANNAF Propulsion Meeting, JANNAF-2015-XXXX, Nashville, TN, June 1-5, 2015.

[9] Katz, I., Mikellides, I. G., Jorns, B. A., and Lopez Ortega, A., "Hall2de Simulations with an Anomalous Transport Model Based on the Electron Cyclotron Drift Instability," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-402, Kobe, Japan, July 4-10, 2015.

[10] Lopez Ortega, A., Mikellides, I. G., and Katz, I., "Hall2de Numerical Simulations for the Assessment of Pole Erosion in a Magnetically Shielded Hall Thruster," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-249, Kobe, Japan, July 4-10, 2015.

[11] Mikellides, I. G., Lopez Ortega, A., Hofer, R. R., Polk, J. E., Kamhawi, H., Yim, J. T., and Myers, J., "Hall2de Simulations of a 12.5-kW Magnetically Shielded Hall Thruster for the NASA Solar Electric Propulsion Technology Demonstration Mission," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-254, Kobe, Japan, July 4-10, 2015.

[12] Myers, J., Kamhawi, H., and Yim, J., "HERMeS Thermal Model," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-XXX, Kobe, Japan, July 4-10, 2015.

[13] Polk, J. E., Guerrero, P., Goebel, D. M., Mikellides, I. G., and Katz, I., "Thermal Characteristics of Lanthanum Hexaboride Hollow Cathodes," Presented at the 34th International Electric Propulsion Conference, IEPC-2015-044, Kobe, Japan, July 4-10, 2015.

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